From Molecular Cores to Planet-forming Disks with SIRTF

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Summary. The *SIRTF* mission and the Legacy programs will provide coherent data bases for extra-galactic and Galactic science that will rapidly become available to researchers through a public archive. The capabilities of *SIRTF* and the six legacy programs are described briefly. Then the cores to disks (c2d) program is described in more detail. The c2d program will use all three *SIRTF* instruments (IRAC, MIPS, and IRS) to observe sources from molecular cores to protoplanetary disks, with a wide range of cloud masses, stellar masses, and star-forming environments. The *SIRTF* data will stimulate many follow-up studies, both with *SIRTF* and with other instruments.

1 Why *SIRTF*?

Much of the radiant energy in the Universe lies in the infrared region, and infrared observations are well suited to the study of distant starburst galaxies and star formation, where dust controls the flow of energy. Observational studies of galaxies and star formation have generally suffered from one or more of the following problems: biased samples, inadequate sensitivity, inadequate spatial resolution, or incomplete spectral data.

The Space Infrared Telescope Facility (*SIRTF*) [8] will provide greatly improved capabilities in the infrared region. *SIRTF* is the last of the series of four great observatories that began with the Hubble Space Telescope and continued with the Compton Gamma Ray Observatory and the Chandra X-ray Observatory. *SIRTF* covers the wavelength region from 3.6 to 160 μm with background-limited performance. Its 85-cm diameter beryllium mirror is cooled below 5.5 K, and the cryogen lifetime should be between 2.5 and 5 years. It was launched on August 25, 2003 into an earth-trailing solar orbit.

The instrument complement includes two imaging array instruments and a spectrometer. The *InfraRed Array Camera* or IRAC, covers 3.6 to 8 μm [7] in four bands; the *Multiband Imaging Photometer for SIRTF* or MIPS, covers 24 to 160 μm [5] in 3 bands; and the *InfraRed Spectrometer*, or IRS, supplies spectroscopy from 5.3 to 40 μm with resolving power $R = 60 - 120$ and from 10 to 37 μm with $R = 600$ [9]. The field of view of the imagers is $5'$ by $5'$ except at 160 μm, where the field of view is $0.5'$ by $5'$. MIPS also has an $R = 15$ spectrophotometric mode between 50 and 100 μm.

2 The Legacy Programs

Observing time on *SIRTF* is divided between Guaranteed Time Observers (GTOs), Legacy programs, and General Observer (GO) programs. The legacy program aims to ensure that coherent data bases of general and lasting value will be obtained during the limited mission lifetime. To enhance opportunities for follow-up with *SIRTF*, the legacy data have no proprietary period; after the archive has opened, about 8 months after launch, data will become available to the public and the legacy teams simultaneously. The legacy teams will provide improved data and, in many cases, ancillary data from other wavelengths and tools for analysis. Legacy programs have typically hundreds of hours of observing time and, insofar as is possible, will be observed early in the mission.

There are three extra-galactic legacy programs and three Galactic legacy programs. The Great Observatories Origins Deep Survey (GOODS) will survey 300 square arcminutes with IRAC and MIPS (24 μm only) overlapping the Hubble and Chandra deep fields. New imaging with Hubble's Advanced Camera for Surveys has been obtained. Extreme starburst galaxies may be detected to $z = 6$ [4]. The *SIRTF* Wide-area Infrared Extragalactic Survey (SWIRE) will map 100 square degrees at high Galactic latitudes with IRAC and MIPS, detecting dusty star-forming galaxies and AGNs to $z \sim 3$ [12]. The *SIRTF* Nearby Galaxies Survey (SINGS) will study 75 nearby galaxies using all the *SIRTF* instruments, providing a template for understanding more distant galaxies [10].

Turning to the Galactic legacy projects, the *SIRTF* Galactic Plane Survey (GLIMPSE) will survey 240 square degrees of the inner Galactic plane with IRAC [1]. The c2d project (described in more detail below) studies nearby low mass star formation and disk evolution [6]. The study of disk evolution is continued to later stages by the Formation and Evolution of Planetary Systems (FEPS) team [14]. The FEPS team will obtain images and spectroscopy of 300 stars with ages from 3 Myr to 1 Gyr.

3 The Cores to Disks Legacy Program

The Cores to Disks (c2d) team includes 11 co-investigators, 34 associates, and 20 affiliates. Associates will work directly on *SIRTF* data; affiliates are adding data at other wavelengths. The goal is to obtain as complete a data base as possible for nearby ($d < 350$ pc) low-mass star formation. The data base will be used to follow the evolution of molecular cloud material from starless cores to stars surrounded by planet-forming disks. The c2d team will observe stars with ages up to 3-10 Myr and will obtain spectroscopy of objects with a range of ages to trace the evolution in the nature of the dust and gas.

Using 400 hours and all three *SIRTF* instruments, the c2d program will provide the most complete data base of infrared observations for low-mass

star formation. Ancillary and complementary data will be collected at wavelengths from X-ray to radio for these same regions. We will map 5 large nearby molecular clouds and 156 compact molecular cores with both IRAC and MIPS (275 hours). Photometry will be obtained for 190 stars with IRAC and MIPS (50 hours). Spectroscopy will be obtained with IRS for at least 170 targets (75 hours).

3.1 A Survey of Nearby Molecular Clouds and Cores

The *SIRTF* mission offers an unprecedented opportunity to determine the stellar content of the nearest star-forming molecular clouds, the distributions of their youngest stars and substellar objects, and the properties of their circumstellar envelopes and disks. Our program will address the questions in the following paragraph.

In the large clouds, we will study the distribution of the youngest stars and substellar objects to understand the conditions needed for their formation. Do isolated cores with associated stars preferentially harbor single stars or small stellar groups? Can brown dwarfs form in the way that ordinary low-mass stars do, or are they ejected from small stellar groups? If very young brown dwarfs are found throughout the cloud, surrounded by envelopes, an extension of low-mass star formation processes into the substellar regime would be viable. Deep IRAC imaging of dense cores will reveal their detailed structure by mapping the extinction of background stars. This structure will be compared with that derived from mapping emission from the dust continuum. The incidence of circumstellar disks in complexes and in isolated cores will elucidate the role of the environment in disk formation. Our less biased sample will allow more robust measures of the lifetimes of various stages in the star formation process. Rare objects and systems in rapid phases of evolution may be present in a large sample. We may, for example, discover the short-lived phase in which the first, molecular core forms, an as yet unobserved stage of star formation [2], [13].

We chose a sample of clouds and cores that will sample a wide range of conditions in order to separate the effects of evolution from other variables. We target five large complexes known to be forming stars in isolation, in groups, and in clusters, and 156 small, isolated cores − 110 starless and 46 with associated *IRAS* sources. The criteria for determining whether a core has an associated "star," meaning a central luminosity source at any evolutionary stage, are similar to those defined by [11].

The molecular cloud complexes and isolated cores will be observed with both IRAC and MIPS at all wavelengths from 3.6 to 160 μm, but we expect the 160 μm detector to be saturated toward these regions. The 3σ limits (based on pre-launch estimates) for the scan maps yield a limit on L_{bol} from 3.6 to 70 μm of about 10^{-3} $L_{\odot}$ at 350 pc. The IRAC bands would detect a 1 Myr old, 5 M_{Jup} brown dwarf at 350 pc, based on models [3].

Through a variety of collaborations, we are extending the data base to both longer and shorter wavelengths. The large clouds and isolated cores are being mapped in the continnum at $\lambda \sim 1$ mm, and in spectral lines. Selected regions have been observed with millimeter-wave interferometers. Further complementary data on the northern clouds in molecular lines and dust extinction and emission are being obtained by the COMPLETE[3] team, who also plan to make the data public. In addition, the large clouds and many northern cores are being imaged at shorter (R, i, and z) wavelengths to limiting magnitudes of 24.5, 22, and 22, respectively.

3.2 The Evolution of Disks up to 10 Myr

Circumstellar disks are the likely sites of planet formation. While disks around T Tauri stars have been studied extensively, much less is known about both very early stages in the formation of disks and their later evolution after accretion has ended. The c2d program on cores and clouds can detect forming disks at very early stages (disks as small as 1 M_{Earth} can be detected through $A_V = 100$ mag). We will also target "debris disks," which are found in association with nearby stars at ages up to about 1 Gyr. We can detect such disks with very small amounts of dust ($\sim 0.1 M_{Moon}$). The timescales for dispersal of disks in such systems are largely unknown.

We will target weak-line T Tauri stars (wTTs) to study disk evolution up to a few Myr. We will address the following key scientific questions. What is the frequency of debris disks in the low-mass stellar population at ages of less than 5 Myr? When does the transition from primordial to debris disk occur? Assaying the full range of disk properties at a given age will help to distinguish evolutionary effects from other factors. Do most disks develop inner holes or gaps during the dissipation process? We will detect evidence for gaps using the spectral energy distribution; the longer wavelengths accessible by *SIRTF* can reveal gaps in the main planet-building zone.

We restricted our sample to wTTs stars that lie within 5° of the nearest large molecular clouds that we are mapping. We also required evidence of youth in the form of X-ray emission or strong Li I 6707 Å absorption. These criteria should allow us to extend the evolutionary stages studied in the clouds to objects with ages up to about 10 Myr. We have worked with the FEPS team to ensure a smooth transition to their program. We will detect excess emisison by comparison to *SIRTF* standard stars and model photospheres. The survey will readily detect disks like that around β Pic, even if they have evacuated inner holes with radii as large as 30 AU. Disks an order of magnitude more tenuous will still be detected if their inner edge is at a radius of 5 AU. We have obtained spectra of the stars in the visible to determine stellar properties and observations with adaptive optics to search for multiplicity.

[3] http://cfa-www.harvard.edu/∼ agoodman/research8.html

3.3 The Evolution of the Building Blocks of Planets

Our spectroscopic program with the IRS instrument will provide crucial information on the evolution in the nature of the materials that build planets, the dust, ice, and gas in circumstellar envelopes and disks. The mid-infrared wavelength range has a wealth of diagnostic features for these three components. *ISO* revealed the potential of such observations for more massive stars, and *SIRTF* will allow spectroscopic studies of solar-type stars. In the 75 hour c2d IRS program, high signal-to-noise spectra will be obtained over the full 5–40 μm range [high resolution ($R \approx 600$) over the 10–37 μm range] for all phases of star- and planet-formation up to ages of $\sim$5 Myr for at least 170 sources. The MIPS-SED mode at 50–100 μm will also be used in the second year of the program to characterize the longer wavelength silicate and ice features of a disk sub-sample.

The IRS spectra can be used to address the following questions. How do spectroscopic diagnostics evolve through the different stages of early stellar evolution? How does the chemical composition of dust and ices change from molecular clouds to planetary bodies? Mid-infrared spectroscopy of disks as the envelope is clearing will be particularly interesting. In the later evolutionary stages, changes in silicate features become the main diagnostics. The spectra will form a powerful data base to compare with spectra of Kuiper-Belt objects, comets and asteroids obtained in other *SIRTF* programs and to clarify the links between interstellar, circumstellar and solar-system material. How does the size distribution of dust grains evolve in circumstellar environments? These observations will permit independent estimates of the dust coagulation and gas dissipation time scales, processes of great importance for planet formation. What is the spectral evolution of substellar objects? The young brown dwarfs and super-Jupiters discovered in the IRAC and MIPS surveys ($\sim$ 100 expected) will be targets for follow-up observations.

We will reserve roughly half the IRS time for follow-up observations of objects found in the mapping programs. The remaining half is scheduled for observations of known embedded and pre-main-sequence stars. We can study objects down to a typical source luminosity of 0.1 $L_\odot$, allowing study of masses down to 0.1 $M_\odot$ at an age of 1 Myr. We plan to achieve a signal to noise of 50–100 on the continuum. This level will allow us to study the thermal history of the envelope through the 15 μm CO_2 bending mode profiles and to search for gas phase emission and absorption features in all phases of star formation. To obtain data with higher spectral resolving power in atmospheric windows, we are conducting flux-limited surveys in the L- and M-band windows using the VLT-ISAAC and Keck NIRSPEC instruments. A subset of IRS targets with known infrared ice absorption features is being characterized, using the CSO and OVRO facilities. The c2d-IRS team will enhance the IRS pipeline data delivered by the SSC in several ways. The most important improvement will be in the defringing of the IRS spectra, because laboratory experiments indeed show the presence of fringes.

4 Summary

The c2d program will provide a legacy for future research on star and planet formation. We hope to provide a data base for unbiased statistical studies of the formation of stars and substellar objects. Data from other wavelength regimes will add to the picture, and modeling tools will assist researchers in using the data base. Follow-up studies of these samples with *SIRTF* itself and with future missions is a natural outcome. The *SIRTF* and ancillary data will be available to the broader community from the *SIRTF Science Center* (SSC), via their Infrared Sky Archive (IRSA). Complementary data products will be made available, as far as possible, through either IRSA or public web sites. Further information on the program, including the source lists, can be found at the c2d website: `http://peggysue.as.utexas.edu/SIRTF/`.

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